TiPS: Results of a Tethered Satellite Experiment

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This paper presents the results of the Tether Physics and Survivability (TiPS) experiment. We provide a description of new analytical tools and methodologies developed for determining the dynamics of the system. A year's worth of laser, radar and optical tracking are combined to provide the history of the librational and rotational motion. The most significant finding from the experiment was that the attitude and rotational motions have damped significantly since initial deployment. A number of tether dynamics specialists have been enlisted to correlate the observed dynamics with theoretical models. In turn enhancements in the tether models are being made as a result of the TiPS data. The results of the TiPS experiment demonstrates the predictability, stability and robustness of tether systems and hint at tethers' potential for space applications.

Figure 1. Partially-Deployed TiPS Experiment

Mission Overview

The idea of using lightweight space tethers was first proposed many decades ago, but only recently have they begun to be deployed in space. Tethers are applicable to a variety of satellite operations including orbital reboost and power generation and offer features available from no other technology. Only a few tether experiments have been flown thus far. Small Expendable Deployer (SEDs) tether systems were successfully released in 1993 and 1994 from Delta upper stages. In these two experiments, the emphasis was on validating tether deployment schemes rather than exploring tether dynamics. The second SEDs experiment survived for several days before unexpectedly being severed, probably due to orbital debris impact. The other two experiments were conducted aboard the US Space Shuttle in 1994 (TSS-1) and 1996 (TSS-1R). Both of these experiments were designed as extensive and well-instrumented investigations of the on-orbit behavior and power generation of tethers. The first experiment was aborted due to a faulty deployment mechanism. The

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second attempt met with much world attention when the tether snapped during deployment. At this time, no tether had survived more than a week. An experiment was now needed to start evaluating the viability of tethers for long life missions.

The latest chapter in the short history of tethers was opened with the release of TiPS. The science objectives for TiPS were to provide information about the dynamics and survivability of a tethered system in space. TiPS was sponsored by the National Reconnaissance Office (NRO) and built by the Naval Research Laboratory (NRL). After an early May launch, TiPS was deployed on orbit at 7:39 GMT on June 20, 1996. As of the date of this report, TiPS has remained intact in its orbit about the Earth for over 400 days. Ground-based tracking of the system has been used exclusively to characterize its librational dynamics. Our most interesting finding is that the motion of the system has damped significantly, from about 40° in-plane and 33° cross-plane to about 7.5° and 5°-7°, respectively. A set of tether dynamics specialists contracted by NRL have been able to model the observed behavior and have used their findings to improve their theoretical models. TiPS is the only tethered system which has provided a long-term history of tether motion.

TiPS was jettisoned into a nominally circular orbit at 552 NM altitude with an orbital inclination of 63.4°. This altitude was selected as a compromise between the experimenters' desire for a long mission life and the domestic space community's fear that the tether could devolve into a four kilometer long "weed-wacker", imperiling other satellites at that altitude. At 8 m^2 of average surface area, TiPS already has a relatively high area-to-mass ratio compared with other satellites. Due to this large cross sectional area, TiPS will experience considerably more drag than a normal satellite and is likely to re-enter the atmosphere in approximately 13 years (the peak of the next solar cycle).

From its earliest stages, TiPS was designed as a low-cost secondary experiment. TiPS was designed to be a passive system. The electronics on board were powered by a short lived battery used to transmit deployment information. This eliminated the need for elaborate power, thermal, attitude and communications sub-systems. The tether dynamics portion of the mission was completed using Satellite Laser Ranging (SLR) data provided by an international network of ground based laser sites. In addition, radar data from the Altair radar on Kwajalein Missile Range (KMR), and optical data from several ground based telescopes contributed to the dynamics knowledge. Each of these data types had specific strengths and weaknesses which made them appropriate for different purposes.

System Description

The fully deployed TiPS payload consists of two bodies: Ralph (the lower end body) and Norton (the upper end body), are connected by a 4023 meter long tether. The drawing in Figure 2 shows the layout and dimensions of the experiment. The SEDS box counted the number of turns of the tether as it deployed, providing a time history of the end body separation following jettison from the host vehicle. The only other equipment on the end bodies are the laser retro-reflectors which allow SLR sites to track the system. As a whole, the experiment weighs less than 130 lbs: Ralph weighs approximately 95.3 lbs, Norton 22.4 lbs, and the tether about 12 lbs.

Ralph was planned to be deployed downward about 980 m from the center of mass and remain the lower vehicle while Norton was to deploy toward zenith. TiPS was expected to maintain this orientation throughout its life. The tether itself is made of a lightweight Spectra-1000 fiber which is 2-3 mm in diameter. Woven in the center of the tether is a yarn to puff up the tether to decrease its susceptibility to catastrophic damage from orbital debris.

Mathematics of Tether Dynamics (Coupled Equations)

A tethered system in orbit experiences two distinctly different motions. The first is the orbital motion of the system which is the orbit of the center of mass about the earth. The second is the librational motion of the end bodies relative to the center of mass. We integrate the orbital motion of the center of mass of the tether system in a reference frame which is fixed at the center of the Earth. For the tether system we choose a local vertical local horizontal (LVLH) coordinate frame rotating with the center of mass of the (see Figure 3). The center of mass is assumed independent of any interaction with the motion of the tether. The motion of the tether, however, is weakly dependent on the orbital motion.

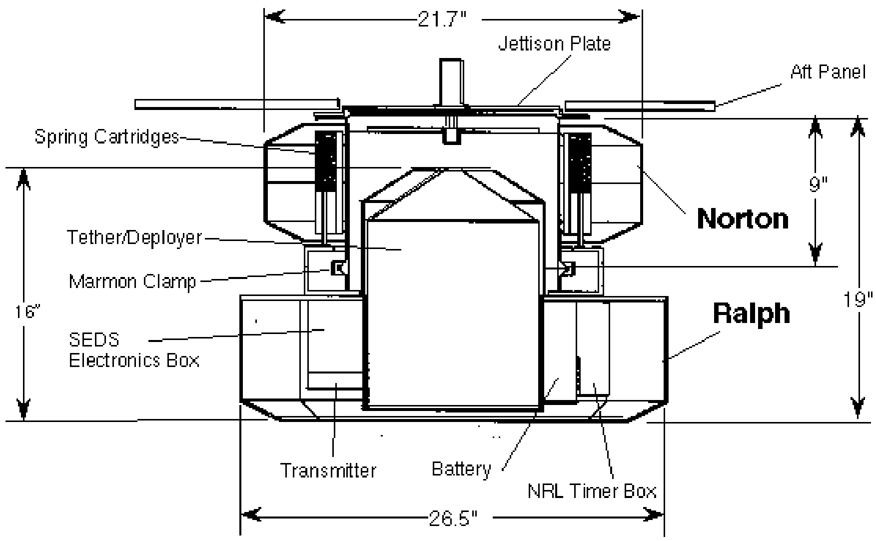

Figure 2. TiPS Schematic

The tether system is modeled as two end masses connected by a massless, extensible tether with longitudinal damping. We refer to Beletsky and Levin [1] for the following set of coupled equations for the tether system.

$$
\begin{aligned}
x - 2wy - wy - (1 + 2k^{-1})\, w^2 x &= (T_x + F_x)/m \\
y + 2wx + wx - (1 - k^{-1})\, w^2 y &= (T_y + F_y)/m \\
z + k^{-1} w^2 z &= (T_z + F_z)/m
\end{aligned}
\qquad (1)
$$

where the stiffness term is given by

$$T_i = (E/r)\ (r/l_{nom} - 1)x_i,$$

where x_i is one of the coordinates (x, y, z), k = 1 + e cos f, w is the angular velocity of the center of mass, m is the mass of one end mass, r is the distance from the center of mass to m_a, E is the extensional stiffness, l_{nom} is the unconstrained length from the center of mass to the end mass, e is the orbital eccentricity, and f is the true anomaly. Although these equations are derived in Beletsky for a small object tethered to a massive (largely stationary) central object, they hold for tether systems in general.

The gravity gradient force acting on the endmass which is implicit in the left-hand side of the equations is balanced by the tension force on the right side. Together they constitute the dominant forces acting on the end bodies. The general forcing function, F, on the right-hand side of the equations can include a variety of perturbing forces such as high order gravitational harmonics, drag, solar radiation pressure, and relativistic forces. For our purposes, we consider them to consist of a single longitudinal damping term caused by the friction between the tether fibers.

A large amount of effort went into developing the software to integrate and differentially correct the initial conditions for the equations in (1). This system was necessary in order to determine the evolutionary changes in the dynamics of the tether and also to provide the SLR sites with acquisition vectors. A complete description of the method of determining the tether motion from observations is provided in [2].

The radial displacement of the tether can be expected to experience a certain amount of damping due to the tether fibers rubbing on each other and other factors. Thus we introduce into our equations a longitudinal damping term which is proportional to the radial velocity of the tether. This is introduced into the equations by

$$F_{xi} \quad = - c\ r\ (xi/r),$$

where we set c to some small positive quantity. Our material engineers provided a range of estimates for this value, none of which significantly effected the predicted system librations.

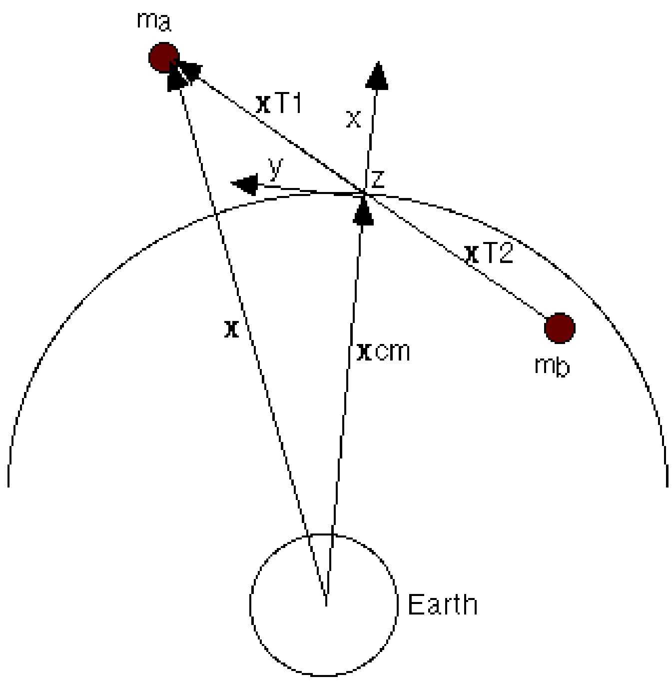

Figure 3. Local Vertical/Local Horizontal (LVLH) system

These equations were first implemented in a 4-5 Runga-Kutta integrator which handled both the integration of the orbital and tether equations of motion. Subsequently, the tether model was incorporated in the NASA-standard orbit model GEODYN, which serves as both orbit/tether predictor and differential corrector. The equations of motion embedded in GEODYN can be integrated in reasonable time on the hardware available to the NRL flight ops team. When sufficient data was available, the team was able to process the SLR and Altair data in a timely manner and produce tether predictions which were accurate for 1-2 days from the time of the last observation.

Data Processing and Acquisition

GEODYN was the primary tool used to determine the orbital and librational parameters from ground based range data supplied by laser and radar. The laser tracking provided our most accurate data, but was difficult to obtain reliably in the desired quantity, in large part due to weather and elevation restrictions. The radar data were less accurate, but provided regular data in much longer tracks and thus was sufficient to produce good predictions for the motion of the system's center-of-mass and gross librational motion. Both of these data sources were primarily useful for the range histories they provided, which typically offered a good gauge of the in-plane motion of the tether. On the other hand, the optical imagery was very useful for obtaining estimates of the cross-plane motion of the tether, but was of little use for prediction and was generally of little use in determining the in-plane motion of the system other than as a validation of the GEODYN predictions.

TiPS laser and radar data generally flows into the processing center at NRL within a day. All of the SLR sites typically contribute normal point data within a day or two, according to their normal operational schedule. This data has been processed at the site to remove obvious outliers and to improve the precision of the data. For an ordinary LEO satellite pass, a site might receive several hundred returns from the target. This data is then reduced to perhaps twenty normal points. This scheme works very well for the other satellites tracked by the SLR network, but does not suffice for discerning our librational motion (for which we would like the full-rate data). As a result of this emphasis on the normal point scheme, there was no mechanism in place at many of the sites to transmit the full-rate data. By special arrangement, our main SLR contributors agreed to send us this data for TiPS. A fortunate consequence of the need for this special procedure was that these sites also agreed to transmit their full rate data immediately after a pass was tracked. This scheme allowed for the most expeditious processing of SLR data.

As a rule, these normal point observations contain only range data. The natural evolution of the SLR data product has led to the elimination of the azimuth and elevation angles from the data stream. The size of the modifications necessary to obtain that data were beyond the scope of the TiPS project.

On the other hand, the passes which would be tracked by radar were very predictable. Whereas the laser sites have to contend with the vagaries of weather, the Altair radar suffered only occasional outages due to higher priority tasking and hardware problems. Its relatively large footprint also made it ideal for overcoming reasonably large uncertainties in the end-bodies positions. With few exceptions, Altair was able to cover two pre-selected TiPS passes each day (one ascending and one descending) using only a NORAD element set. Following each day's ascending pass, the radar data was transmitted to the processing site. This data consisted of azimuth, elevation and range measurements. The only difficulty with Altair was that it is a highly sought-after deep space tracking asset. Consequently, obtaining coverage was both difficult and somewhat expensive. We received approximately 2 passes per day during two months, April and again in July of 1997.

The combined radar and SLR data were next processed in GEODYN to produce a one week prediction for the orbit and tether motions. The orbit prediction is converted into a set of top-of-the-hour (TOH) vectors, consisting of the Earth Centered Inertial (ECI) position and velocity of the TiPS center-of-mass. The TOH vectors and seven top-of-the-day (TOD) tether state vectors are sent to the central SLR office at NASA's SLR processing facility located at Allied Signal (ATSC) in Greenbelt, Maryland. The processing of the TiPS TOH vectors follows the same procedure as that used for the other satellites tracked by the SLR network. Each day's TOD vector for the center-of-mass is converted into ECF coordinates. The week's set of seven TOD vectors (referred to as tuned Inter-Range Vectors (TIRVs) are then deposited into an account on a VAX mainframe along with the TOD tether states.

At the start of the next shift at the ground site, a shift operator retrieves the new TIRVs and tether states from the central site's mainframe and transfers them to the station's workstation. There, each of the TIRVs is integrated to generate a one day ephemeris listing for the CM's trajectory at one minute increments. The ephemeris listings contain both ECI and ECF coordinates and the mean Greenwich hour angle (uncorrected for UT1). For each pass scheduled to be tracked, the points of closest approach (PCAs) are identified and saved for use in combining the orbit and tether motions.

In a separate operation, the tether motion is integrated with a smaller time step. The tether equations described previously were incorporated into an on-site integrator which allowed the ground sites to model the motion of the tether end-bodies. This model was installed and validated by site personnel at the NASA stations, Starfire and Herstmonceux. (The other participating sites did not install this software because of the time and cost involved.) Both Starfire and Herstmonceux were able to integrate the model with the ground controller software. Unfortunately, since the computing power and flexibility of the NASA ground controllers was somewhat limited, the tether motion could not be fully incorporated into their tracking software. Instead of modeling the tether motion throughout a given pass, the position and angular velocity of the tether system at PCA was used to generate the offsets from the center-of-mass for each end-body. This resulted in some loss of accuracy in the tether predictions but could not be improved given the resources available.

Using the ECI vectors for the CM, the tether offsets were added to generate the predicted end-body positions. The predicted end-body positions were then processed through a polynomial fitting algorithm to generate a set of coefficients used by the ground controller for locating the end-bodies in azimuth, elevation and range. The pointing angles generated by the polynomial could then be fed directly into the mount hardware to orient the laser. The predicted range generated by the polynomial is used to set the photodector's range gate for each laser pulse. This gate allows for uncertainty in the arrival time of the pulse by opening the photodector 3 μsec before the expected return time of the pulse and closing it 3 μsec later. If the target is in the line of sight, we are reasonably assured of getting a return if the targeted satellite is ±450 meters from its expected position in range and within the laser footprint in azimuth and elevation. Prior to the pass start, the shift operator checks any existing time bias history to determine the best starting point for the pass. The time bias is an operator's means of measuring the intrack prediction error.

Evolution of the Orbit and Libration Determination Procedure

The purpose of the orbit and libration determination effort was twofold. The more important of the two goals was to validate existing tether models and gain understanding of the long-term dynamics of orbiting tethers. For this purpose a time history of the TiPS system's libration and orbit motions was sought. The secondary objective was to determine whether acquisition of TiPS could be performed like that for other SLR satellites. The former goal was essentially achieved by the first anniversary of the TiPS deployment. The later objective was met with some qualified success, but the results achieved did indicate the type of resources necessary to achieve the goal more completely.

Determining the history of the TiPS system's librational and orbital dynamics was of interest for several reasons. The main question was whether the initially large amplitudes of the in-plane and cross-plane libration, 35 and 40 degrees, respectively, would decrease with time and if so, how fast. All of our data sources (SLR, radar and optical) were combined to obtain the libration amplitude history shown at the end of this section. The findings led directly into a search for damping mechanisms. Examination of the optical tracking also permitted an investigation into anomalous tether dynamics. Finally, when the large scale orbit and libration motions were removed, an investigation was performed to identify both the rotation rate of the end-bodies and higher order motions in the tether (e.g. skip-rope modes, transverse waves) using the ranging data.

The orbit and libration determination procedure became fairly well-defined relatively early in the TiPS flight. While it proved extremely difficult to obtain accurate simultaneous solutions for the orbit and libration motion over continuous observation periods longer than four to six hours, (which was insufficient for a stable orbit prediction) other techniques were developed to separate the orbit and libration determination functions. The ranging data from the SLR and radar sites were processed using both long-arc and short-arc reduction schemes which could be combined to present a coherent picture of system's behavior. These techniques relied on "freezing" portions of TiPS dynamics in order to analyze the remaining motions. The use of optical data, while not initially planned, revealed itself to be a useful means of extracting data on librations, primarily on the cross-plane motion. Use of the optical data effectively side-stepped the orbit determination (OD) aspect of the problem.

Long-Arc Orbit Fit

The first step in the processing of the range data was to perform a long-arc (ten to twenty day observation span) orbit determination to characterize the gross orbital motion. The tether was forced to remain aligned with nadir throughout the run in order to complete the integration in reasonable time. (Simultaneous integration of the orbit and tether equations required an order of magnitude more time than an orbit-only integration.)

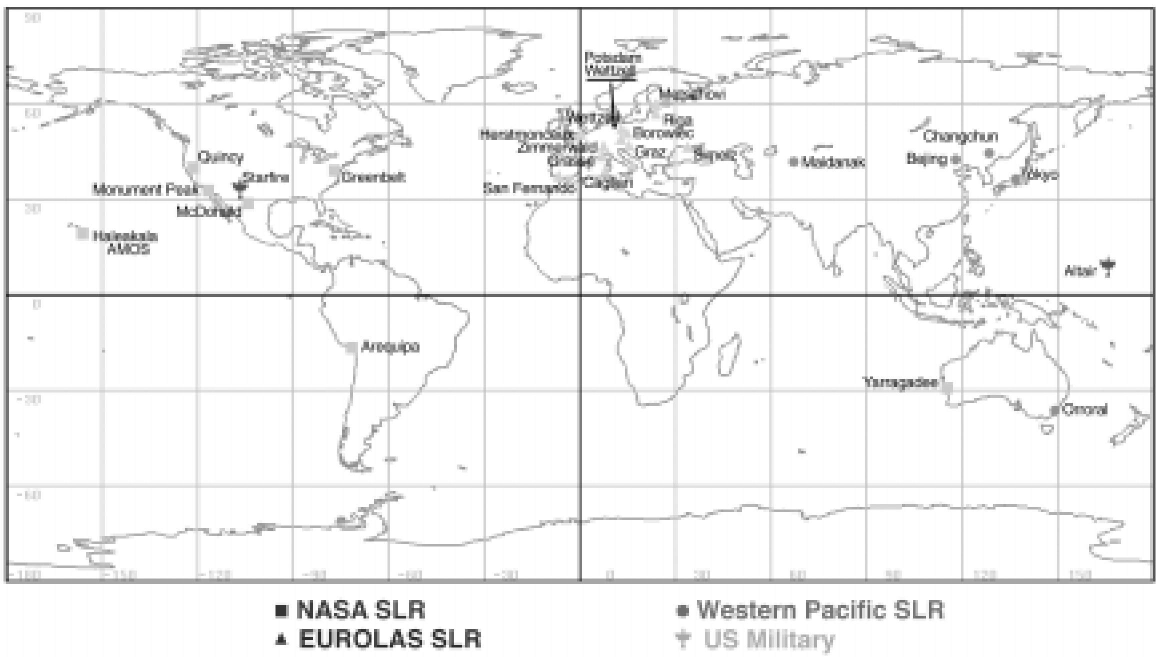

Figure 4. TiPS Tracking Network (SLR/Radar/Optical)

A pair of more complex adjustments were performed to model the tether's length properly. These included both known and suspected effects of the tether motion. First, any empirically observed length adjustments were performed. These were based on the short arc tether motion fits which will be described later. Essentially, these corrections compensated for unmodeled tether motions (e.g. jump rope and transverse wave modes) and uncertainties in knowledge of the tether's deployed length. Secondly, the tether's length was artificially shortened to account for the apparent difference in end-body altitudes which result from the libration. This was performed by combining the linearized probability distributions for the in-plane and cross-plane motions to compute an effective shortening along the local zenith direction. For example, if the tether were believed to be librating with a six degree in-plane and cross-plane motion, the tether's length would be shortened by 22 meters (0.55%). If the tether were librating at twelve and eight degrees in the in- and cross-plane amplitude, respectively, then the shortening was set to 63 meters (1.57%).

As long as the data set comprises a geographically-diverse group of passes, the tether motion will appear as noise. Although our tracking data came overwhelmingly from Northern Hemisphere sites (see Figure 4), we were often able to obtain a good distribution of tracking with respect to latitude. If this had not been the case, we ran the risk of a systematic skewing of the orbit determination process due to coupling between the orbital and librational motion. Given an adequate amount of coverage, the results of the initial center-of-mass run were usually accurate enough to identify any incorrectly tagged data.

A somewhat better fit was then obtained using an empirically-determined drag estimate. The calibration of our drag model was a major consideration in our efforts to track TiPS. This was entirely predictable given the high area-to-mass ratio for the system. The two line element sets provided by US Space Command had always exhibited a very large along-track drift (about one second per day). This was reported both the amateur astronomers who tracked TiPS and by the SLR sites who had to resort to the use of those element sets for acquiring TiPS when sufficient SLR and/or radar data were not available. During May, 1997 we were able to improve our drag modeling to the extent that our TiPS predicts maintained a time bias drift of less than 10 millesecond/day over a week. This level of accuracy generated the only significant numbers of daylight passes tracked during the TiPS experiment.

The drag modeled during the May tracking period was 23% higher than expected. The original baseline for the drag model assumed a drag coefficient of 2.3 with a total surface area of 9.75 square meters. This included the highest a priori area estimate from the manufacturer. At large libration amplitudes, the tether's orbit-averaged surface area could be expected to decrease. This effect, however, would have tended to decrease the drag experienced by the system. (The largest libration motion believed to exist during this period would have caused an effective decrease of less than 1% in this area.) Similarly, the tether's manufacturer professed no belief that the material would expand beyond 2.2-2.3 millimeters in diameter even after prolonged exposure to the LEO environment. While there was no reason to expect that the drag coefficient was especially large for the tether, it was the most effective mechanism for improving the fidelity of our fit to the observations.

The drag coefficient was determined using fixed observation spans of ten and twenty days for several time periods during the month of April, 1997. For these orbit determination runs the drag coefficient was varied in increments of 0.05 from 2.2 to 3.2. The initial condition determined from each trials were then used to predict the motion of the TiPS system over the next week. This predict was then tested against the observation which were collected during that week. In each case, the best fit to the new data was obtained using drag coefficients of either 2.9 or 2.95. A second set of trials with a finer resolution resulted in our selection of a drag coefficient of 2.915. As noted previously, this estimate worked extremely during the following May. In the following chart (Figure 5), the improvement in time bias drift obtained with the new drag parameter is seen to be substantial.

Unfortunately, this drag correction was not constant for all of the TiPS orbit determination arcs. In other instances, the optimal drag coefficient could be as much as 12% lower or a few percent higher. In this context, the drag correction was perhaps less a calibration of the drag parameters for the spacecraft as it was a sponge term for temporal uncertainties in the atmospheric model or other unmodeled effects.

Short Arc Libration Determination

Once best fit for the long arc center of mass determination run has been completed, candidate single pass libration determination opportunities were identified. The easiest to identify candidates were the radar passes which tracked the system down to at least 15 degrees in elevation on either the up or downside. Since observations existed for both end-bodies a reasonable solution could usually be developed. Other likely candidates were twenty to twenty-five minute periods in which two or more sites were tracking simultaneously or near simultaneously, with at least some of the tracking on the upper end-body. Finally, any SLR passes in which the site obtained a minimal five minute duration pass with 3-4 subtracks on each end-body were investigated.

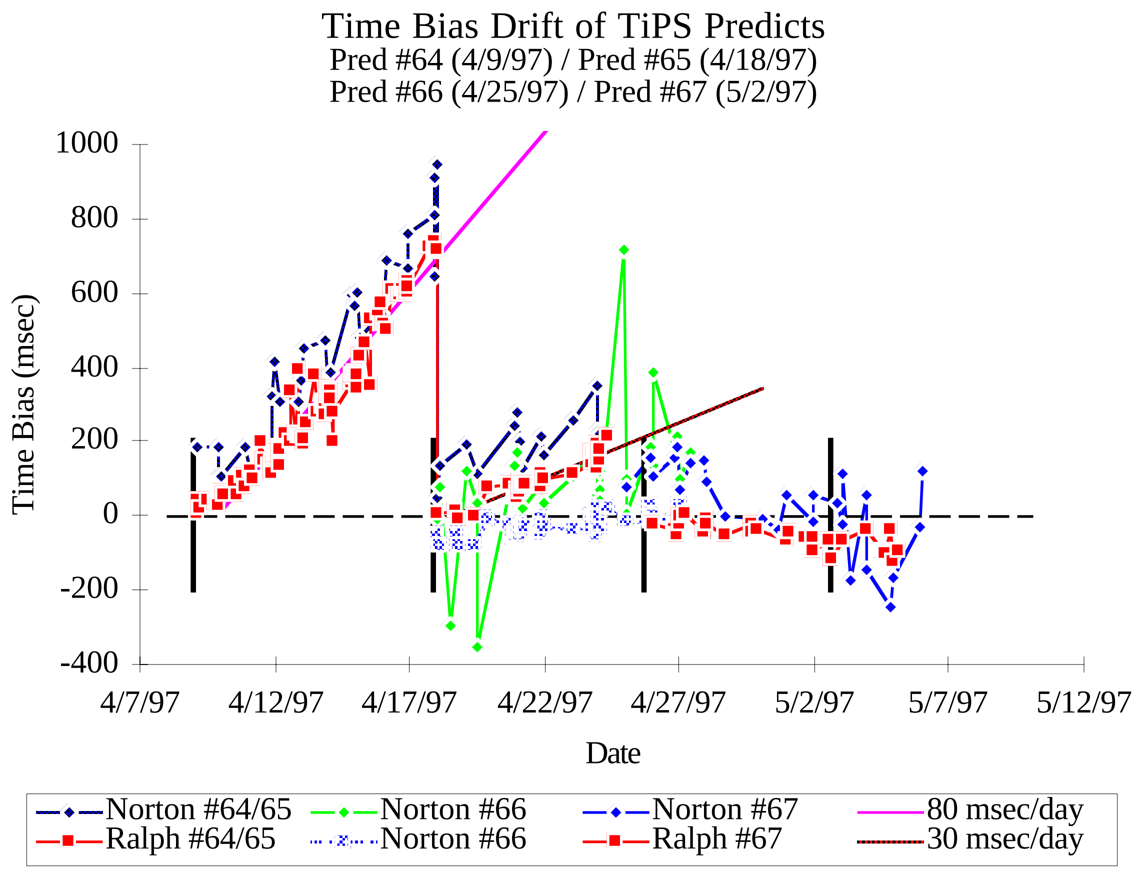

Figure 5. Best-Fit Drag Modeling Led to Improved Tracking in May 1997

For each identified period, the initial conditions for the orbit were taken from the long arc CM run and the tether was initialized to be oriented along nadir. The orbit/libration determination run then proceeded with freedom to alter the libration angles and rates for the tether, and limited freedom to change the inclination, node and mean anomaly of the orbit. This approach was chosen because the long arc CM run was known to be most substantial to errors in these three parameters. The results of this first run were usually not entirely satisfactory in that the predicted libration amplitudes were unrealistic. The next stage of processing frequently involved the manual deletion of a substantial number of data points and a more tightly constrained set of orbit initial conditions for the next OD run.

About 40% of the radar passes produced promising enough results to prompt further investigation, while the same could be said for about 20% of the SLR-only passes. Virtually all short arc passes containing laser and radar data were pursued. Frequently, two or three iterations were all that were needed to converge on good results with the radar data. Also, the greater noise on the observations made excessive manipulation of the data or orbit constraints impractical. On the other hand, much greater efforts were typically required with the SLR-only data. When results were achieved, however, the accuracy of the SLR-based findings were deemed substantially higher.

The essential problem with the SLR data was that the results of the orbit/libration determination were frequently ambiguous. Depending on the selection of initial conditions, very different answers could be derived which fit the observations to the 20-30 meter level. There were, however, typically patterns in the range residuals which indicated that some long-period motion was not being modeled correctly. If the data set looked promising enough, these cases were pursued using a brute-force approach.

The advantage of having data on both end-bodies becomes apparent at this point, as range errors manifest themselves very differently for libration and orbit errors. A similar situation exists for the difference between in-plane and cross-plane errors. Simply put, in terms of range residuals, orbit-induced errors will tend to appear the same for either of the end-bodies, while libration errors will tend to appear different. If the tether were actually moving opposite to the expected direction, the range residuals would show them separating in range space. As an example, consider Figure 6, which clearly shows the range residuals characteristic of an orbit state error.

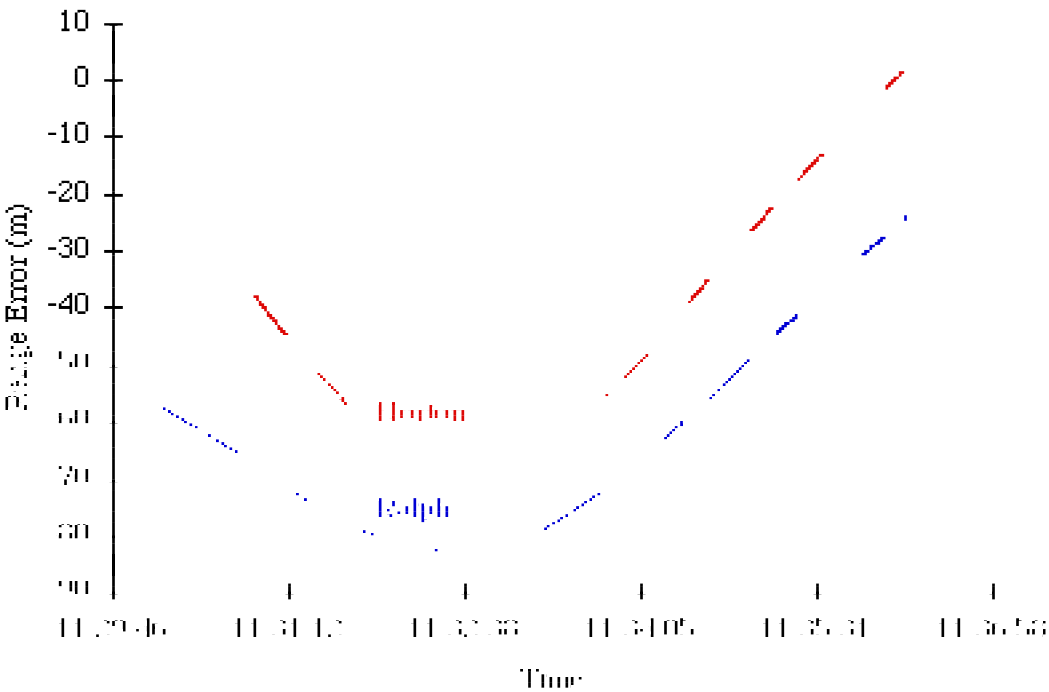

Figure 6. Day 232 (8/19/96) Residuals

Once the errors in the orbit/libration motion were separated, it was much easier to dissect the errors in the orbit state using a brute force approach since the number of parameters which needed to be varied was much lower. Typically a fine mesh search was performed for fixed values of inclination first. The best-fit inclination was then selected and constrained for the remainder of the next few iterations as the node and along-track position were investigated. Once the most obvious orbit errors had been removed, there was often the obvious signature of some sort of tether motion remaining.

Depending on the length of the arc and the number of stations tracking, the remainder of the search could require a great deal more effort. Particularly at the large in-plane amplitudes, the tether motion was highly non-linear. The chief problem was getting near enough to the actual initial conditions for GEODYN to converge. The search procedure eventually amounted to assuming an amplitude for the in-plane and cross-plane motions and trying to guess in what phase each motion was by observing its signature in the residual data. While not a very efficient process, gratification was very perceptible when a truly solid solution was found. In particular, once the orbit and tether motions were determined, it was possible to observe the actual rotation of the end-bodies, as shown below in Figure 7.

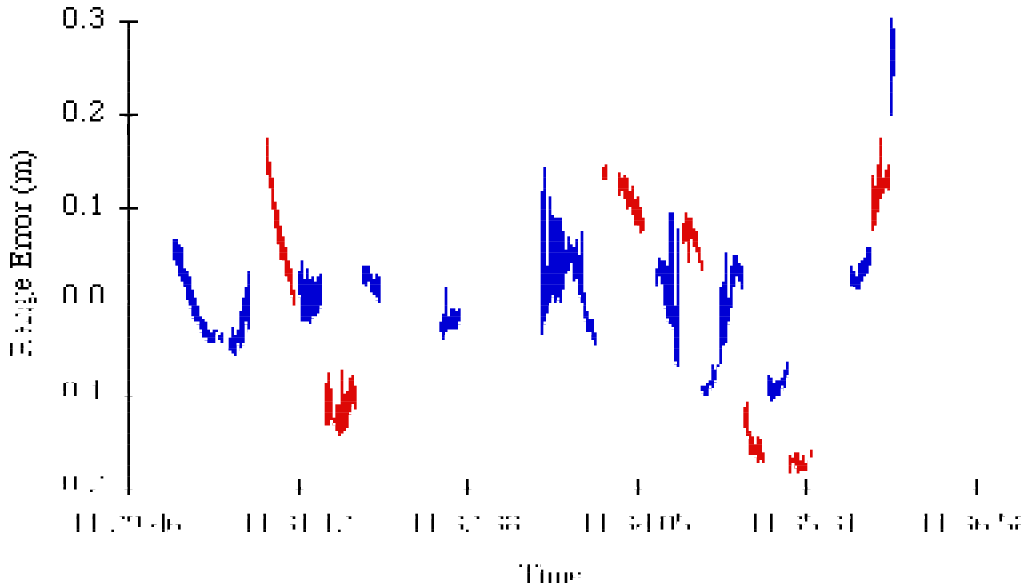

Figure 7. End-Body Rotation Visible in SLR Data.
Day 232 (8/19/96) Starfire Switching Between Endmasses

Libration Determination from Optical Observations

The processing of ground based optical images of TiPS proved to be a valuable data source. It's most important feature was that it was an inherent complement to the range data. Range measurements provided information about motion occurring along the observer's line of sight. Conversely, optical data allowed characterization of motion in a plane perpendicular to that line of sight. The findings gathered from analysis of the optical data were able to validate the range data findings and to provide some insight into tether dynamics when deterministic results were not available. Furthermore, only optical observations could be used to examine the shape of the tether itself.

The optical processing technique developed by NRL is based on matching the tether and orbit orientations shown in a video frame to a computer simulation of the telescope view. In the computer simulation, the tether orbit is propagated to the time of the observation, and the tether attitude is adjusted by hand to match the orientation shown in the video frame. This yields one possible set of in-plane/cross-plane angles that exists along an indeterminate line of possible solutions. At best, a point solution of the in-plane or the cross-plane angle can be determined from a single frame but never both. A point solution is the instantaneous measure of the angle. The reason both angles cannot be determined from a single frame is because we are not using any information on the apparent length of the tether. This is due to difficulties in determining the field of view from the multitude of sensors that observed TiPS and that the entire length of the tether is not always in the frame. However by taking multiple frames from a single pass, combined with a knowledge of the period of the tether's motion, we were able to reduce a series of indeterminate solutions to a single amplitude solution.

The quality and type of the solution obtained is largely dependent on the geometry of the pass being analyzed. Very high elevation passes give the best measurement of the cross-plane component of the tether's orientation. For these passes, when the tether is close to the horizon, it is often very easy to discern the cross-plane angle while being nearly impossible to get any measurement of the in-plane angle. Additionally, very high elevation passes often last for fifteen minutes or more, during which time the tether has passed through more than one quarter of its librational motion. By getting measurements of the cross-plane angle at both the beginning and end of these long passes, combined with knowledge of the librational period it becomes rather straightforward to deduce the cross-plane amplitude. On the other hand, low elevation passes tend to give the best measurement of the in-plane instantaneous angle. On these passes, there always exists a point near the maximum elevation of the pass that the instantaneous in-plane angle could be clearly measured while being unable to measure any of the cross-plane orientation. Unfortunately, on these low elevation passes, it is difficult to get multiple measurements of the in-plane angle separated by enough time to be able to deduce the amplitude of the in-plane motion.

There are a number of factors that restrict the utility of processing these optical observations. The first and most obvious of these is weather. This technique primarily relied on observations from the Starfire Optical Range (SOR) in Albuquerque, NM and the Maui Space Surveillance System (MSSS) in Hawaii. Both of these sites had extended periods of many weeks when observations couldn't be made. Also, on many occasions a pass could be recorded with partially clear skies. On these passes, point solutions could sometimes be obtained, but if a significant portion of the pass was lost due to clouds, achieving an amplitude solution wasn't possible. The second limiting factor was the lighting of the tether. The ground telescopes needed to have terminator lighting to be able to record a pass. For the sites mentioned above, there were periods of about three to four weeks when they could image TiPS, followed by about two months when they could not. There were also passes where the TiPS orbit was partially eclipsed, which eliminated enough of the pass to make it impossible to obtain an amplitude solution. Another limiting factor was the quality of the image/videotape. For the tape to be usable, it needed to have a timestamp to be displayed in the frame, have stars visible in the background and preferably have the entire length of the tether visible. The timestamp is needed so that the computer simulation could propagate the TiPS orbit to the time of the observation. Stars or star streaks are needed to be able to measure the direction of the velocity vector. The velocity vector's orientation is needed so that the simulation image can be rotated about the telescope line of sight to match the rotation of the image that the various telescope mounts introduce. By using these star streaks we've eliminated the need to model the mount rotations in NRL's visualization program. Lastly, it was preferred that the entire length of the tether was in the field of view, as early in the mission the tether had a fair amount of bow and viewing a small portion of the tether would not give a good indication of the end mass positions. This condition often resulted in some of the best data coming simply from acquisition telescopes.

Deployment Data

During deployment, the SEDS box recorded the deployment of the tether as Ralph and Norton separated. The downlinked telemetry was compared to data recorded during the winding of the tether. Provided in Figure. 8 is length and length rate recorded during deployment. After separating at the expected 4.3 m/s, the separation rate was slowed by friction between the tether, canister and spool. Deployment was completed 42.5 minutes after separation. The length rate at full deployment was approximately 2.1 m/s.

Confirmation of separation was provided by optical sensors at Starfire. A pictorial history of the Starfire 1.5 meter observations is available on the NRL TiPS website[4]. SLR data obtained from Starfire was used to verify Norton's rotation rate at separation.

SLR Tracking

The global SLR network consists of over forty systems, six of which are managed by NASA. Currently, the global SLR network tracks seventeen retro-reflector equipped satellites launched by a variety of countries. The current system was designed primarily for the study of crustal dynamics and the Earth's ocean and atmospheric systems. As such, the system has been developed into an extremely accurate source of range data [3]. The most advanced SLR systems can generate single shot range accuracy at the level of several centimeters and can process that data into normal point ranges with accuracy's of a few millimeters. Even the oldest of the systems are accurate to less than a meter in a single shot and to half a meter or less in the normal point data.

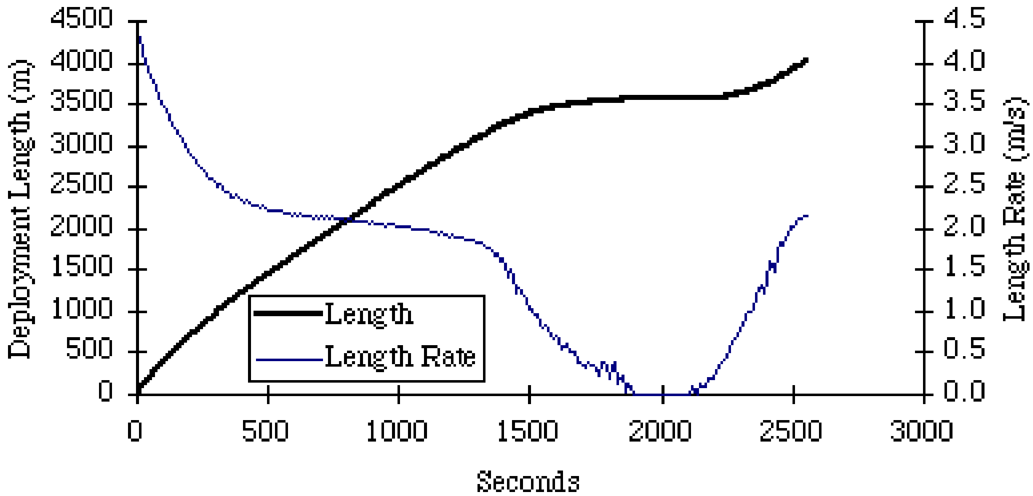

Figure 8. Deployment Length and Length Rate

For most ordinary (i.e. point mass) laser-ranged satellites, the process of tracking and orbit determination becomes routine following a brief period of intensive searching. The collection of SLR data is then subject to only a few constraints. As a rule, SLR sites do not range below 20 degrees elevation to prevent contact with aircraft. This constraint was even tighter at Starfire and for the Greenbelt night passes, when the elevation restriction was increased to 30 degrees. A second constraint was the obvious need for clear weather - which usually translates into the loss of 30-40% of the available passes. Additionally, some sites do not to range during daylight or in adverse climatic conditions such as high humidity or strong winds. Finally, many of the sites are not staffed continuously. Their schedules are optimized for coverage of the TOPEX altimetric satellite, which may or may not be in phase with the satellite of interest.

TiPS was an anomaly for the SLR network in at least two major senses: First, it is the only non-point mass satellite being tracked by SLR. This was a fundamentally new type of system for them. Second, as explained earlier, it is also the only system without a consistently accurate predicted ephemeris. The overwhelming majority (99%) of the TiPS SLR passes were acquired with a spotter telescope and terminator assistance. In this situation, depicted in Figure 9, the station is in darkness and the tether is illuminated. As a result, our SLR coverage was strongly related to the presence of an orbital geometry which produced good terminator coverage. In Figure 10, we plot the expected terminator pass opportunities and tracked passes for the last year. In this figure notice the two high peaks. It was during these two periods we augmented SLR tracking with radar tracking from Altair.

Over the life of the TiPS experiment, a set of 27 SLR sites have successfully tracked a total of 1637 passes. Of these, 1171 were on Ralph and 466 were on Norton. On average, each pass lasted 3.6 minutes.

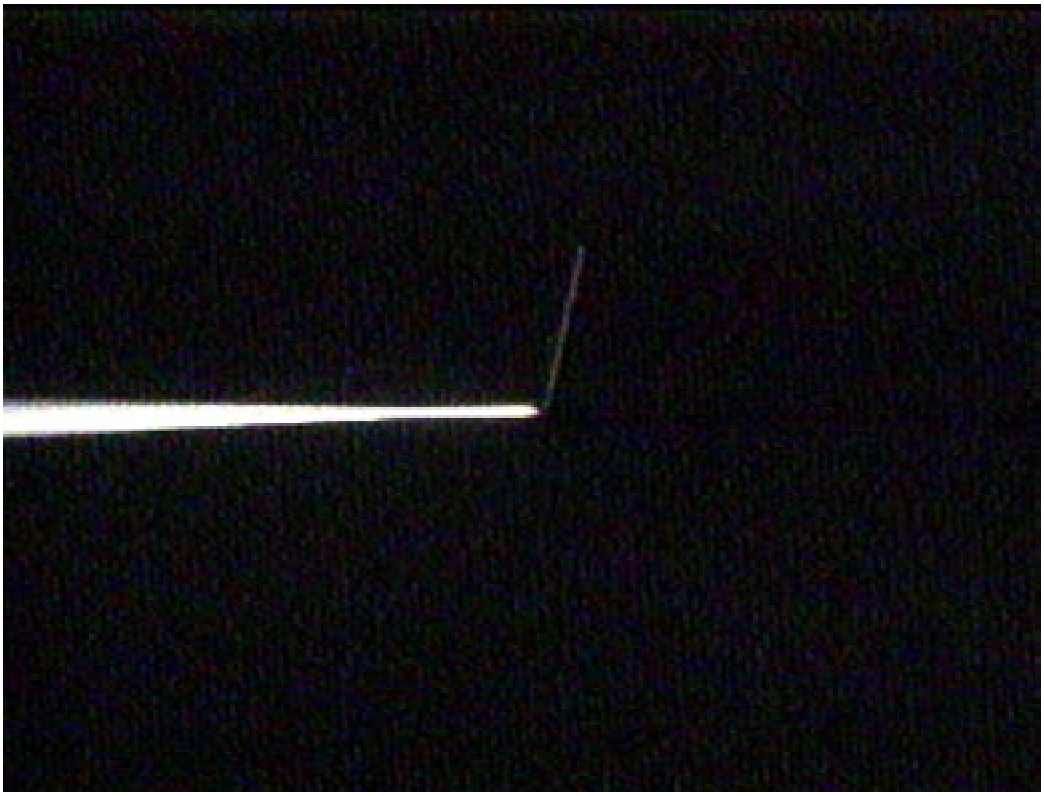

Figure 9. Frame Grab of Spotter Scope Display. Ralph End Body Being Ranged by NASA's MOB-7 at 8:30 GMT on 6/22/96 (Laser Beam Enters from Left of Screen.)

The majority of our SLR tracking came from a small group of European and NASA stations. The ability to track TiPS was largely dependent on the presence of either of two capabilities: the presence of good optics or a large beam divergence. The former enabled a site to aim their pulses precisely. In the later case, systems with larger beam divergence tolerated bigger errors in the predicted ephemeris. The NASA systems had beam divergences of 100 microradians, which created a 150 meter wide footprint at the TiPS altitude. Additionally, being able to set a wide range gate, to tolerate more range uncertainty) increased the odds of getting observations.

Virtually all of the passes, especially in the early phases of the flight, were taken on only one end-body, usually Ralph. After some early success with dual-ranged passes using Starfire, the sites that were able to alternate tracking within a pass were asked to obtain multiple subtracks during each pass. Riga, Herstmonceux, Potsdam and Monument Peak were adept at this task. Though it was possible to determine the libration using only data on one end-body, as a practical matter, it was only achieved when data were available for both.

Through simulations we were able to determine that a combination of node and inclination errors can mimic range residual errors due to a poor estimate of the tether motion. In fact, due to the short pass duration and the fact that the orbit and tether motions have similar periods, any tether error can be masked in orbit error and vice-versa. Similarly, we have found that even with a perfect estimate of the orbit, errors in the tether state become clear only at the lower elevations. For this reason it is difficult to estimate tether state from SLR data.

The simulated data shown in Figure 11 compare the effect on Norton's range residuals of orbit and tether state errors. The results shown here were created for a 4/20/97 pass over Altair with a duration set as the average length of an SLR pass. It was also typical of the SLR data received in that the track started near PCA at an elevation of 65 degrees and continued down to 25 degrees. First, a reference orbit was computed with zero tether motion. Then, a superimposed in-track libration was added to the reference motion with a 7.5 degrees in-track amplitude to generate the tether residuals,. Cases in which the tether was either swinging forward through nadir (a phase of 0 degrees) or at its forward-most limit (phase angle of 90 degrees) at the start of the track were plotted. The orbit errors were generated by subtracting 0.01 degrees from the nominal inclination and adding 0.0023 degrees to the orbit node. The residuals for the orbit and tether errors have virtually identical signatures when the tether phase is set to 35 degrees.

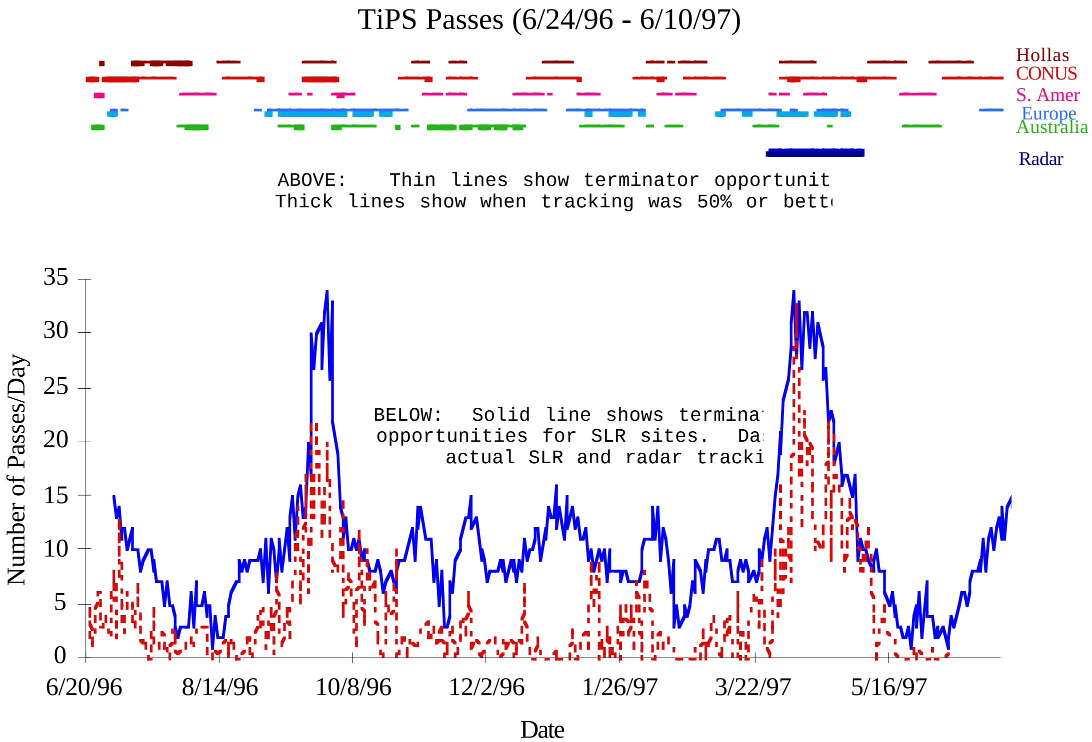

Figure 10. TiPS SLR Tracking Strongly Correlated with Periods

Radar Tracking

The radar data consisted of azimuth, elevation and range data from the Altair facility at the Kwajalein Missile Range in the Marshall Islands. It is typically considered a deep space asset and is generally accurate to tens of meters in range. During a five week period in April and May, 1997 and again for a four week period in July, 1997, the radar provided two tracking passes a day for TiPS. In contrast to most of the laser sites, Altair had very little difficulty switching between the TiPS end-bodies and was also able to track the dipole near the center of the TiPS system.

On average, each Altair pass consisted of seven distinct subtracks on each of the end-bodies. Altair was able to track at elevations of a few degrees which permitted passes often in excess of fifteen minutes long. Compared with the situation with the SLR data, we are now covering a significant fraction of a libration period which causes clear trends to emerge in the range residuals. The noise in the range measurements (see Figure 12) were larger than the laser data, but were more than accurate enough for libration determination.

Although the range residuals are not as sensitive to errors in the cross-plane tether state estimate, these too become clearer at the longer observation spans, particularly with the presence of data on both end-bodies.

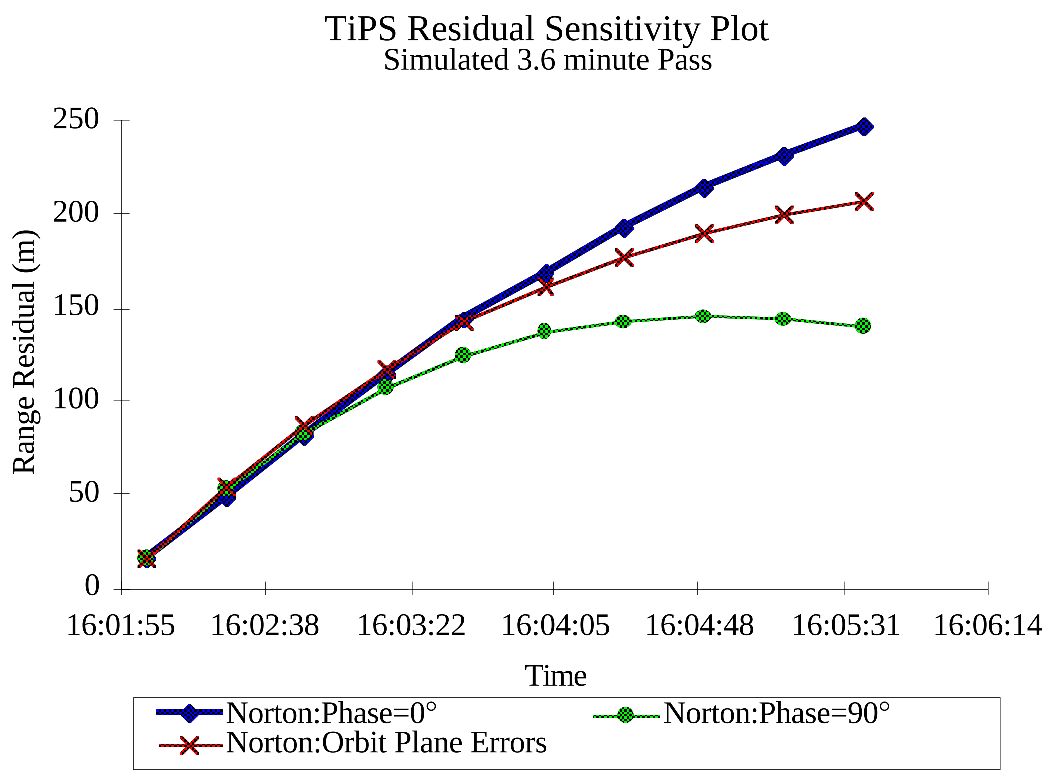

Figure 11. Tether and Orbit Errors Exhibit Similar Signatures

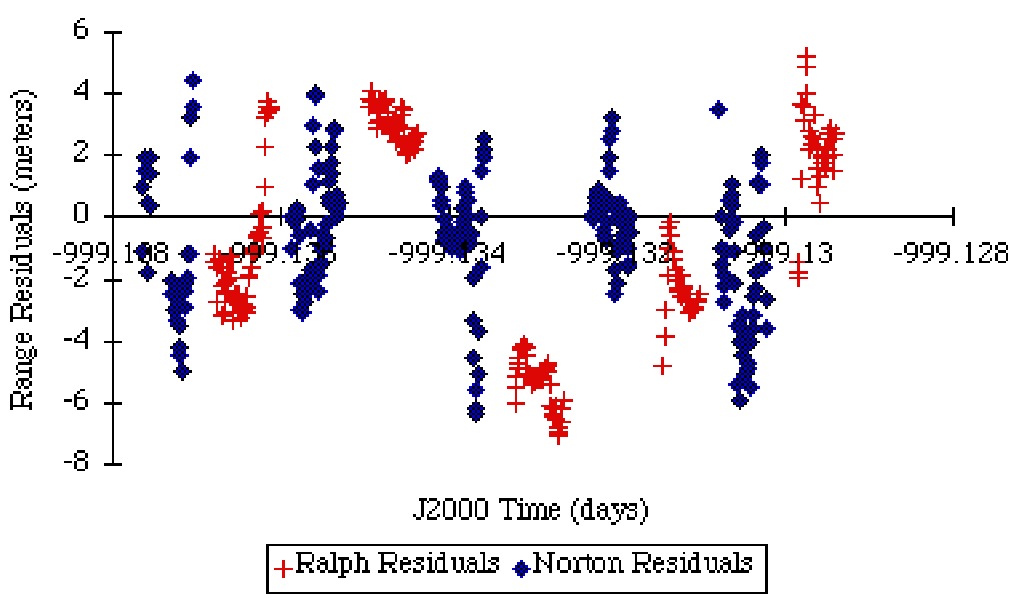

Figure 12. Range Residuals on a 16 minute Altair Pass

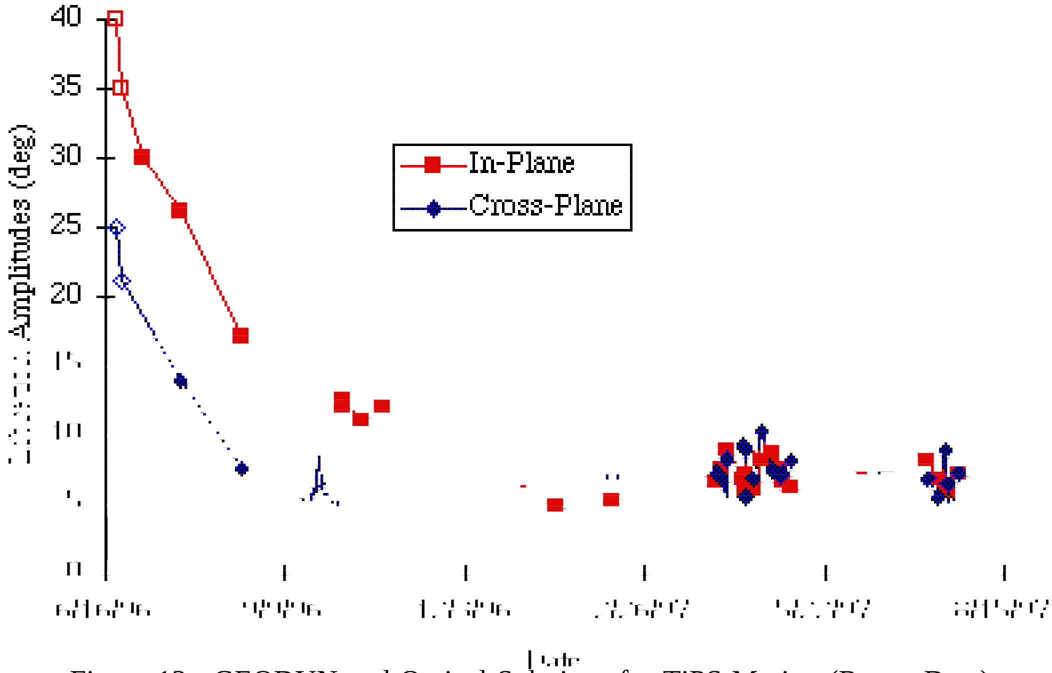

Figure 13. GEODYN and Optical Solutions for TiPS Motion (Range Data)
Solutions Constructed from Optical Data are indicated by Hollow Symbols.

Findings

Figure 13 shows the TiPS libration amplitude history as determined from the SLR, radar and optical data. As of July, 1997, the initial amplitudes of the TiPS motion are believed to have decreased from their initial values down to 7.5°±2° in the in-plane component and 5°±2° degrees in cross-plane amplitude. The mechanisms of that decrease are discussed in the next section.

TiPS Optical Processing Results

Table 1 summarizes the amplitude solution findings of the optical processing. There were also numerous instantaneous point solutions found and they are detailed on the TiPS website[4], a subset of those that occurred during deployment are listed in Table 2. Note that the error bars listed were not empirically derived, rather represent the analyst's judgment on the quality of the result. During deployment on June 20, 1996, five point solutions were obtained. These cross-plane values are all in the 30°-37° range, higher than was expected from the deployment, and the error at ±10° was also larger than what was later achievable but is believed to bound the range of cross-plane angles the tether experienced during this time. Also note that in Table 1 the first two measurements of the amplitudes are from the second and fifth day of the mission, a time when the amplitudes of both components of motion were quite a bit larger than later observed. September of 1996 was a period of intensive tracking of TiPS, both from the SLR network, and optically from the MSSS. The cross-plane amplitude solutions obtained during this time all have a good confidence attached to them at ±2° and are indicating approximately the same cross-plane amplitude. This seems to indicate that the cross-plane motion had reached its apparent steady state by this time. A number of in-plane point solutions were also obtained in September, and this was one of the rare times when there was intensive tracking from both SLR and optically. During this time there were numerous successful blind comparisons between the predictions derived from GEODYN solutions and the optical solutions. This provided a validation of each method. Additionally, the point solutions obtained throughout the mission, while not being conclusive in being able to define amplitudes of the tether motion, support the amplitude solutions obtained from GEODYN in that they were in almost every instance of smaller magnitude than those amplitude solutions.

TiPS Visual Inspection

An added benefit of using optical data for dynamics studies is that it affords numerous opportunities to study the tether shape. During deployment the tether appeared to be deploying very straight. However by the second day of the mission, a bow could be very clearly seen, estimated to create ~200 m of shortening, on which several kinks or higher order modes also clearly visible. Observations on subsequent days continued to show a bow of the same magnitude, but the many kinks observed were not again visible and are assumed to have been deployment transients. The next period when many observations were made was late September of 1996, approximately 100 days into the mission. At this time the magnitude of the bow appeared to have halved and was well behaved. On some passes a second order mode was observed, but was very slight and difficult to see. Additionally during this period it was noticed that from pass to pass that the bow wouldn't always appear in the same quadrant, as measured about the centerline of the tether. In fact during the week and a half of observations in late September the bow was observed in all four quadrants. By the next period of observations in February of 1997, the tether appeared almost perfectly straight and it was almost impossible to discern any bowing of the tether. It has been in this state for all subsequent observations.

Observation Time	In-Plane	Cross-Plane
6/21/96 9:26	40°±7°	25°±15°
6/24/96 9:30	35°±7°	21°±7°
9/21/96 6:05		5.2°±2°
9/23/96 5:36		6.6°±2°
9/25/96 5:07		8.5°±2°
9/26/96 15:12		6°±2°
9/29/96 14:14		5°±2°
2/11/97 6:07		7°±2°
4/6/97 6:21		5.5°±2°
7/20/97 15:36		5°±2°

Table 1: Amplitude Solutions from Optical Data

Observation Time	In-Plane	Cross-Plane
6/20/96 10:36:35		35°±10°
6/20/96 10:38:20		37°±10°
6/20/96 10:42:43	9°±10°	
6/20/96 10:45:50		35°±10°
6/20/96 10:48:35		30°±10°

Table 2: Deployment Point Solutions from Optical Data

Rotation Rate History (End-Bodies)

The precision of the SLR data made possible determination of the rotation rates of the TiPS end-bodies. The 18 retroreflectors on each of the end-bodies were placed such that there would be a retroreflector within 30 degrees of any incident beam, with 6 in each of three rings spaced 60 degrees apart. This was to insure that enough signal strength would be available for tracking. This arrangement does not however give a clear indication of the location of the center of mass (CM). Adjacent retroreflectors physically are of different ranges to the observer. Depending on the orientation, this can be many centimeters. The nominal spin axis of the endmasses is along the tether. This will present a spinning parallelogram of retroreflectors to the observer. From this basic geometry, two cycles of range changes will be observed for each revolution of the endmass. Nominally, 6 of the 18 retroreflectors will return the laser beam during one rotation.

During deployment, the NRL tracking team at Starfire Optical Range (SOR) was able to range to Norton. Given that the system was spinning about the tether axis at 4 rpm and the parallelogram shape of the endmass, we would expect that the period of the range change would be 7.5 seconds. Figure 14 shows the residuals to a polynomial fit of the raw ranging measurements. The period of the range changes appears between 6.4 and 6.8 seconds. Due to unknown orientation of the endmass and the apparent change of orientation due to the azimuth change during the collection of these measurements this is in agreement with the expected period. Six days after deployment, the NRL laser ranging team at SOR was able to track both endmasses, alternating the dwell time on each. The observed periods are roughly 14.2 seconds for both endmasses suggesting that the rotation rate of the system was 2.1 RPM, half the initial rate. This is shown in Figure 15.

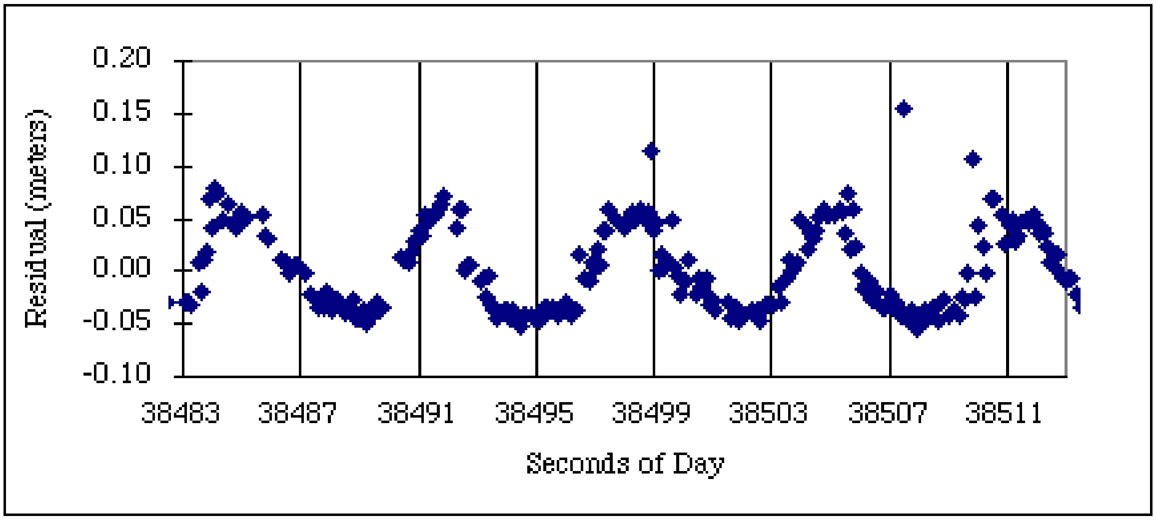

Figure 14. Norton Range Residuals during Deployment

Subsequent measurements have been analyzed for many passes. We describe here representative data sets collected over the mission.. The NASA Moblas 8 site at Quincy, CA tracking of ralph on day 190 of 1996 indicates a period of 19.2sec (1.6 RPM). By day 265 of 1996, NASA Moblas 7 at Greenbelt MD indicates a period of 48-56 seconds (0.6 RPM). By day 277 of 1996, Wettzell, Germany indicates periods of 72-84 seconds (0.36 to 0.4 RPM). The tracking opportunities are finite, and measurement of these periods begins to approach the length of the tracking so as the rotation rate slows down, the determination of the rotation rate becomes difficult. On long tracks in April, 1997, the data showed that the motion was so slow that no period of rotation could be determined. Although the period of the rotation cannot be determined from this data, the amplitude of the residuals is very large. This could only occur if the laser were being reflected from different retroreflectors during the pass. Thus, it is believed that Ralph is still rotating at a very slow rate.

Modeling of Long-Term Dynamics

Several tether dynamics experts were enlisted to study the TiPS flight data. The experts were tasked to try to replicate the observed long term behavior with analytical simulations. The goal was to provide insight into the physics governing long term tether dynamics. The primary interest was in understanding the observed damping in both the in-plane and cross-plane libration amplitude. The analysts' results agreed with one another quite well and replicated much of the observed behavior.

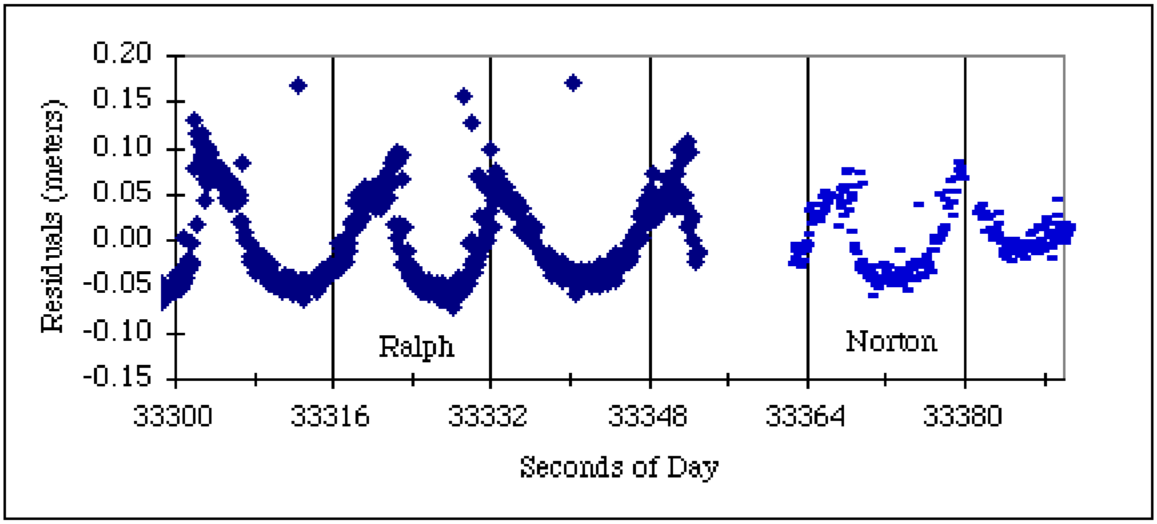

Figure. 15. Ralph and Norton Residuals for Day 178

The various analytical simulations arrived at the same predictions for the TiPS behavior while using different techniques and software codes. This concurrence confirmed that each was modeling the same basic physics. The simulations showed that a tether system starting at an in-plane libration above 40° would damp in two distinct phases. The early phase was distinguished by the fact that almost all damping would occur in the cross-plane libration, with very little damping in the in-plane libration. The later phase would have no damping in the cross-plane while there was steady, exponential damping in the in-plane libration. It was also observed that there was a periodic, coherent relationship between the in-plane and cross-plane libration trajectories in the early phase that was not present in the later phase. This periodic relationship derived from the fact that the ratio of in-plane period to cross-plane period is 5:4 for high libration amplitudes. This periodic relationship with the 5:4 period ratio disappears for in-plane amplitudes below 37°. The physics and mathematics of this behavior is beyond the scope of this paper.

The predicted behavior matches of the TiPS data however there is one significant area of disagreement. The best estimate of the TiPS behavior is that cross-plane amplitude damped from ~30° to a steady state value of about 7° in the first two months on orbit. The in-plane libration damped from 40° to a steady state value of about 8° over the first 7 months on orbit. The libration amplitudes have not changed noticeably for the latest 6 months on orbit. This shows that the TiPS libration amplitudes followed the two phase behavior demonstrated in the predictions. The predictions typically could be made to match the in-plane data or the cross-plane data histories but could not be made to match both simultaneously. The predicted time history of the behavior was largely dependent on the magnitude of the selected damping parameters. If the damping parameters were set such that the in-plane history matched well, then the cross-plane amplitude would have a steady state value of about 20°. The damping parameters would have to be set quite low for the cross-plane steady state amplitude to settle at 7°. However, with these low damping parameters the damping would take place much slower than that observed. The general trend was that as the damping factor increases then the in-plane damping occurs faster and the cross-plane steady state level would be higher.

In summary, there was no value for the damping parameter that would make the simulations match all of the TiPS observations. There are three possible explanations for this mismatch: 1) Incorrect observations of TiPS, 2) Some unmodeled damping phenomena or 3) Inaccurate modeling of the transition from the early phase to the later phase. Regarding point #1, the TiPS data has been well corroborated by verifying the optical method against the GEODYN method. However, there is roughly 25% uncertainty for each amplitude solution, especially in the early data points. Regarding point #3, the different methods used different damping sources, one used viscoelastic, another used coulomb friction and a third used a generalized dissipative factor, yet all three predicted the same behavior. This shows that the damping response of TiPS is the same regardless of how energy is extracted from the system. Regarding point #2, it is possible that there was some as yet undetermined phenomena that rapidly removed energy from the system during the early phase so that the cross-plane amplitude could reach the steady state value of 7° while the rest of the damping occurred more slowly. The TiPS mission simply did not return enough data to resolve this conflict..

Conclusions

The TiPS mission and this analysis is the first detailed investigation of long term tether dynamics to our knowledge. The dynamics analysis correlated fairly well, but not perfectly with the flight data. There was not enough quantity or the accuracy of libration solutions in the early flight data to resolve the one conflict between theory and data. Both flight data and analytical simulations showed stable damped behavior. It is important to note that neither the in-plane nor the cross-plane libration amplitudes have changed since the first eight months of the mission.

Acknowledgments

The authors would first like to thank the ground station personnel at all of the sites in the global network who provided the data that enabled TiPS to achieve its goals. In particular, we wish to recognize the EUROLAS community, especially Dr. Kasimir Lapushka of the Latvia University and Dr. Andrew Sinclair of the Royal Greenwich Observatory for their active involvement in supporting this experiment. At Altair Radar, Kwajalein Missile Range, Gary Duff, provided valuable data at short notice. The Starfire Optical Range generously provided tracking data and optical support. We are grateful to the Maui Space Surveillance System for help in understanding optical tracking and for their image processing software, IDPS, provided to help analyze the data. We are indebted to the Vandenberg Air Force base and Paul Swanson for providing telemetry downlink support during deployment. Further, we want to thank Chris Rupp and NASA Marshall Space Flight Center for providing the tether deployer and the SEDS electronics box which provided telemetry during the TiPS deployment.

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